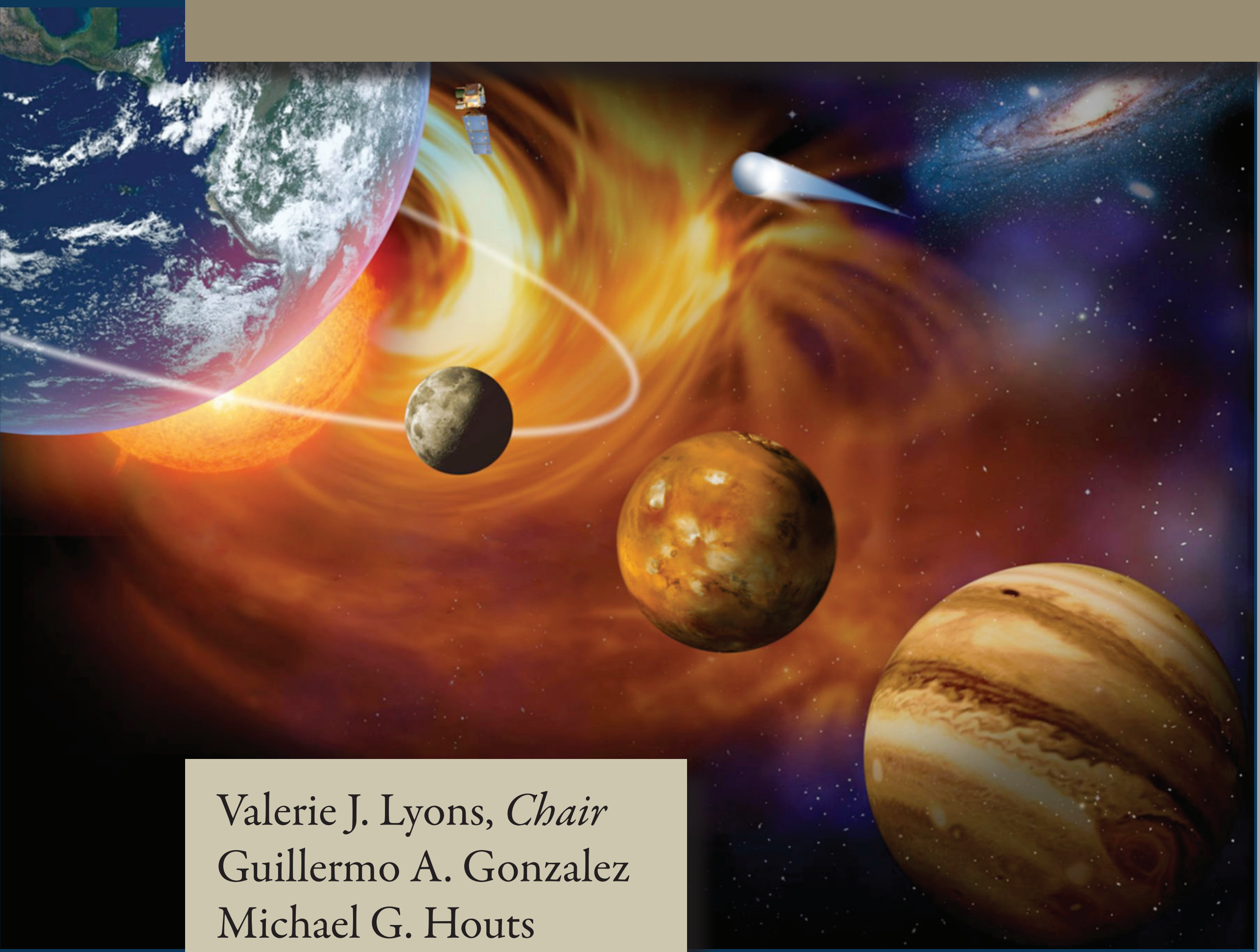
National Aeronautics and Space Administration

Space Power and Energy Storage Roadmap

Technology Area 03



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 03 input: Space Power and Energy Storage. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

The purpose of this study is to assess space power and energy storage technologies and formulate a roadmap (Figure R) and a Technology Area Breakdown Structure (Figure 3 – discussed in more detail in Section 2) which can guide NASA's investments to assure the timely delivery of innovative and enabling power and energy storage systems for future space missions, while also providing tangible products for aeronautical and terrestrial applications.

The state of practice power systems are heavy, bulky, not efficient enough, and cannot function properly in some extreme environments. The proposed power technology will provide power systems with significant mass and volume savings (3 to 4X), increased efficiency (2 to 3X) and enable operation at low and high temperatures and extreme radiation environments. These advanced capabilities will enable power and energy storage for future science and exploration missions such as: missions using electric propulsion, robotic missions, lunar exploration missions to NEO and MARS, crewed habitats, astronaut equipment, robotic surface missions to Venus and Europa, polar Mars missions and Moon missions, and distributed constellations of micro-spacecraft. Space power systems also offer benefits to other national needs. This includes national defense systems such as unmanned aerial vehicles (fuel cells, batteries, wireless power), unmanned underwater vehicles (AUV's) (batteries, fuel cells, PMAD), and soldier portable power systems (PV, batteries, wireless power, PMAD). Benefits to the terrestrial energy sector include: all-electric and hybrid cars (batteries, fuel cells, etc.), grid-scale energy storage systems (batteries, electrolyzers, fuel cells, flywheels, PMAD, etc.), smart grid (PMAD, analytical tools), terrestrial solar power systems (high efficiency solar cells, advanced arrays, PV calibration, solar concentrators, Stirling convertors, systems analysis), advanced nuclear power systems, green energy systems (alternative fuels, advanced PMAD for wind/solar systems, energy conservation analysis, etc.), and remote, off-grid power systems (crewed vehicles and habitats).

The study team reviewed the: 1) National Space Policy of the USA (June 2010); 2) NASA strategic planning document; 3) SMD next decadal mission options; 4) Human Exploration Space System (HESS) of ESMD; 5) Aeronautics research directorate mission planning document. The Office of Chief Technologist identified critical design reference missions to guide the technology teams to develop critical technology needs for future missions. The team considered the following missions of SMD that require advanced power technologies: Jupiter/Europa, Saturn /Titan, Neptune, Pluto System Missions; the NEO/Small body Missions: Comet Nucleus Sample Return, the NEO SEP robotic mission; the Inner Planetary Missions: Venus Surface and Venus Sample Return missions; Mars Missions: Mars In-Situ Resource Utilization (ISRU), Mars Plane, Surveyor and Mars Network Landers. The ESMD missions that require advanced power technologies are: crewed HEO mission, long duration EVA's, astronaut suits, crewed NEO SEP/NEP missions and Mars missions. The Space Operations Mission Directorate requires advanced power technologies to perform ISS upgrades which will include integrating updated power and energy storage systems to extend the power system lifetime to match the longer ISS mission. Finally, the roadmap includes the power technology needs of the Aeronautics Mission Directorate for "more electric" airplanes that will rely on power and energy storage technologies for reducing fuel burn and emissions.

1. GENERAL OVERVIEW

The purpose of this study is to assess the state of practice of space power and energy storage technologies and formulate a technology roadmap that can guide NASA's investments to assure the timely development and delivery of innovative and enabling power and energy storage systems for future space missions. The major power subsystems are:(1) Power Generation/ Conversion, (2) Energy Storage, and (3) Power Management and Distribution (PMAD). Power generation/ conversion subsystems include solar arrays, radioisotope power generators, reactor power systems and fuel cells. The energy systems employed in space missions include batteries, regenerative fuel cells and capacitors. PMAD includes power distribution and transmission, conversion and regulation, load management and control.

Power systems are characterized by a number of performance parameters. One parameter of great importance is specific power (W/kg) that indicates how much power can be delivered per unit mass of power system. Other related parameters include specific energy (Wh/kg) and energy density (Wh/m^3). However, power systems are not always amenable to simple characterization in terms of a single variable such as specific power. Other ancillary features can be equally important. These might include temperature sensitivity, stowed volume, cycle life, storage life, radiation resistance, etc. As space missions shift more and more from orbital missions to in situ missions with their harsh environments, these other factors become more important.

When viewing the power technologies in the roadmap schematic (shown previously in Figure "R"), the technology milestones (shown in blue) are at technology readiness level 6. They are assumed to be ready in 4 years (on average) for mission use and then are displayed as new capabilities (in orange). The milestones which intersect with key propulsion technologies are shown as orange with black centers. These technologies will then be incorporated into the sample missions (green milestones) as either mission "pull" (shown by the dotted green lines) or "push" (where the new capabilities can eventually enable or enhance a mission).

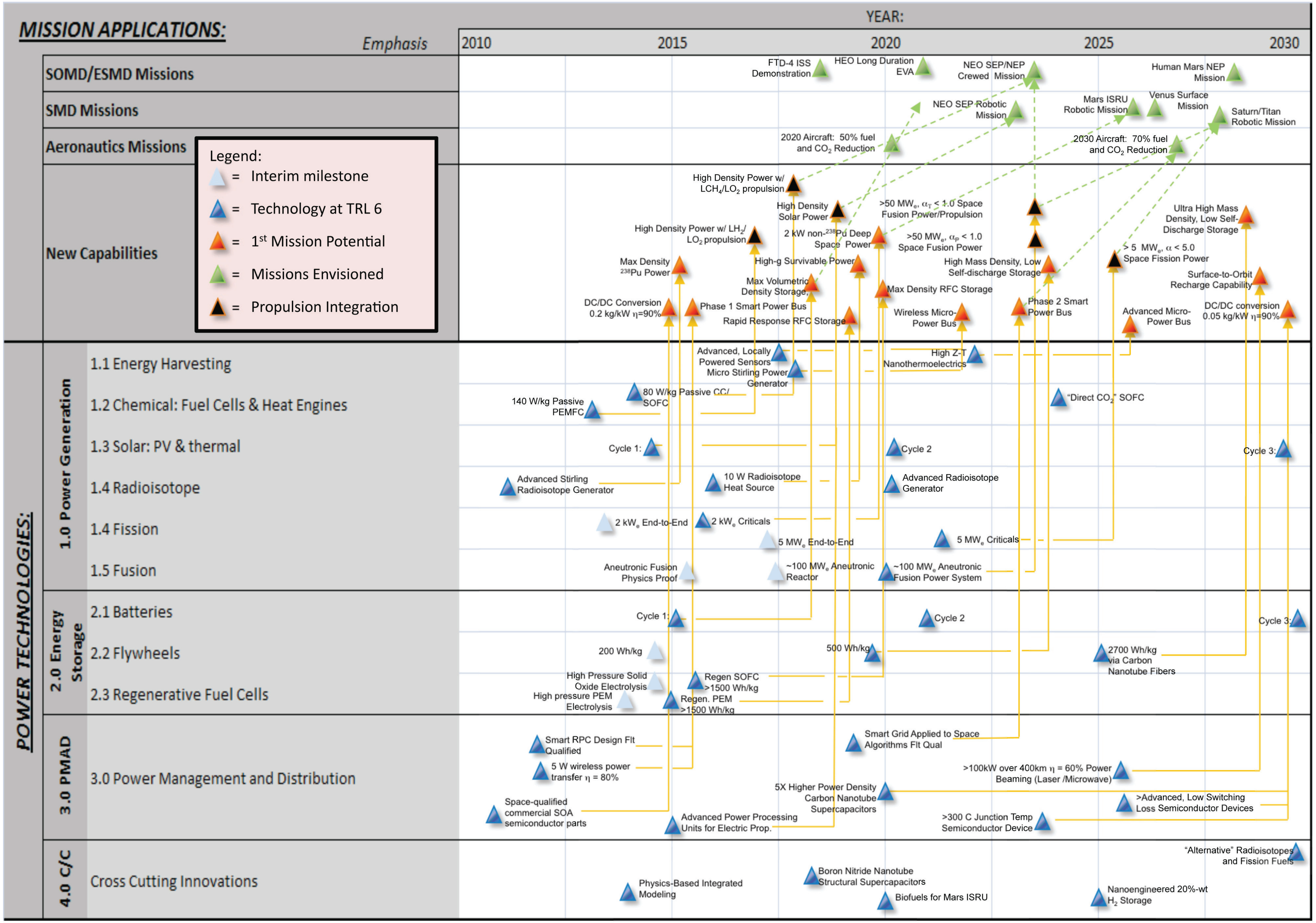
1.1. Technical Approach

The road map lays out general technical approaches for advancing the state of the art in power generation, energy storage, power management and distribution, as well as their cross-cutting technology areas. For power management and distribution (PMAD), the major philosophy associated with the road map is to focus on semiconductor device advances resulting in increase breakdown voltage, reduced switching/conduction losses, and improved junction temperature and radiation tolerance. These advances would be most cross cutting and have the greatest impact on PMAD, enabling revolutionary improvements in conversion systems. In addition, the road map emphasizes advances in power beaming as well power system architecture improvements which are enabled by advanced fault isolation and smart algorithms for control.

In solar power generation, the emphasis is on the development of high efficiency cells, cells that can effectively operate in low intensity/low temperature (LILT) conditions (> 3 AU), cells and arrays that can operate for long periods at high temperatures (>200°C), high specific power arrays (500-1000 W/kg), electrostatically-clean, radiation tolerant, dust tolerant, and durable, re-stowable/deployable arrays. Development of chemical power generation systems should focus on the development of PEM and solid oxide fuel cell plants with passive reactant and water management. Development of small (~2 kW), high reliability heat engine plants (e.g., Stirling, Brayton, Rankine) for use on the exhaust of solid oxide fuel cell plants should also be pursued as an option for maximizing specific energy in power generation from methane propellants. Radioisotope Power System (RPS) work should focus on ensuring an adequate supply of ^{238}Pu, making efficient use of available ^{238}Pu, and developing a 10 Watt class radioisotope heat source that could be used on a variety of missions including sub-surface probes. Power conversion technologies that should be further developed include advanced Stirling and advanced thermoelectric. Work will focus on improving RPS efficiency and specific power while ensuring long life (minimum 14 years). If it appears that adequate ^{238}Pu will not be available, it may be necessary to investigate the use of alternative isotopes. RPS work will help enable advanced science missions and new capabilities, such as long-life subsurface probes and radioisotope electric propulsion. Fission Power System (FPS) efforts should focus on continued technology development for a 10 – 100 kWe "workhorse" system, development of a 500 – 5000 W_e fission system for use on advanced science missions and (potentially) some "flexible path" missions, and development of technologies to enable very high power (> 5 MW_e) very low specific mass (< 5 kg/kW_e) space fission power. Work on low power (< 100 kW_e) fission systems should focus on researching and developing methods for integrating developed technologies into a highly useful, long-life power supply. Work on high power (> 100 kW_e) fission systems should focus on advanced fuels and materials, and high temperature power conversion. FPS work will help enable affordable use of fission systems for missions not currently possible. These include missions requiring >1000 W_e in hostile environments (e.g. heat, dust, radiation) or in regions where adequate sunlight is not available (e.g. outer planets, permanently shaded craters, high Martian latitudes, etc.). Technology work related to high power fission systems will help enable high performance nuclear electric propulsion for cargo and human missions to any destination desired. Fusion power generation technology development should focus on ~ 50 MW aneutronic (p-^{11}B) reactors, direct power conversion (e.g., traveling wave) from high energy charged particle beams, high voltage (~1 MV), high efficiency power management and distribution. Related propulsion work should focus on the development of plasma thrusters in which the plasma is heated directly by the high energy charged particle beam from an aneutronic fusion reactor.

In energy storage, the technical approach to de-

Figure R: *Space Power and Energy Storage Roadmap*



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velop advanced space batteries focuses on the development of: 1) High specific energy and long life rechargeable batteries (500 Wh/kg, 5000 cycles), 2) High specific energy low temperature rechargeable batteries (200 Wh/kg, -100°C), 3) high specific energy primary batteries (1000 Wh/kg) with low temperature operational capability (-160°C), 4) high temperature (450°C) primary and rechargeable batteries, 5) green battery materials and processes; and 6) advanced electronics to implement optimized charge methodologies to enhance life and safety.

For flywheel energy storage, development should focus on flywheel component miniaturization, nanotechnology-based rotors, magnetic bearings, reliability, and system development and demonstration.

In order to develop high specific energy, high efficiency, and long life, regenerative fuel cells (RFC), work should focus in the following technical areas: 1) trade studies on the selection of most promising RFC systems for a specific application (Alkaline, PEM and Solid oxide); 2) development of high efficiency fuel cells and electrolyzers; 3) reactant storage system mass reduction; 4) improved water and thermal management subsystems; 5) design and fabrication of integrated RFC systems; and 6) test and validation.

In the cross-cutting technology area, some identified technical approaches include multi-functional structures, physics-based modeling of power components and systems, nano-technology based super-capacitors and hydrogen storage capability, biofuels and alternative nuclear fuels for power sources, and the impact of green energy systems development both in the aerospace and terrestrial communities. Thermal issues are a concern for all power systems and are addressed as part of the technology development for each power component and working with the TA-14 Thermal Technology Area.

1.2. Benefits

Technology advances in space power and energy storage offer significant benefits to spacecraft, rovers, spacesuits, tools, computers, habitats, communication networks, and anything that requires power and energy storage. New missions are enabled when a breakthrough in power generation or energy storage is attained. For instance, if a novel photovoltaic system is developed that can operate in low intensity, low temperature conditions, space systems can be solar powered farther from the sun. If a nuclear power system is developed that is cost effective and lightweight, our space exploration will not depend on solar energy and we can further our knowledge of outer planetary science. Advanced power systems enable high power robotic and crewed electric propulsion missions as well as in-situ resource utilization missions (ISRU). They enhance the capabilities of crewed exploration vehicles (for LEO, HEO, NEO & Mars missions) and crewed surface habitats. Advances in power system durability and life enable missions with high radiation and extreme temperature environments (e.g. Venus, Europa, Mars polar, Lunar polar science missions). Miniaturization of power systems, improving impact tolerance for landing and creating novel power system architectures enable nano-satellites and small planetary probes.

Aeronautics benefits from space power and energy storage products when they are used to produce a more-electric, fuel efficient aircraft. Advanced power and energy storage technology can enable missions that are limited only by our imagination.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

The study team reviewed the NASA strategic goals enabled by space power and energy storage, including the Science Missions such as the Outer Planetary Missions: Jupiter/Europa, Saturn /Titan, Neptune, Pluto System Missions; the NEO/Small body Missions: Comet Nucleus Sample Return, the NEO SEP robotic mission; the Inner Planetary Missions: Venus Surface and Venus Sample Return missions; Mars Missions: Mars ISRU, Mars Plane, Surveyor and Mars Network Landers. The Exploration Mission Directorate will need this technology for their Crewed HEO mission, Long Duration EVA's, Astronaut Suits, Crewed NEO SEP/NEP Mission and Mars Missions including the Nuclear Electric Propulsion Human Mars Mission. The Space Operations Mission Directorate will need to perform ISS upgrades which will include integrating updated power and energy storage systems over its now-longer lifetime. The Aeronautics Mission Directorate is interested in "more electric" airplanes that will rely on power and energy storage technologies for reducing fuel burn and emissions.

1.4. Top Technical Challenges

When viewing the system level challenges, the power system composes 20-30 percent of the spacecraft mass based on studies by Joseph Sovie of NASA's Glenn Research Center (Figure 1). This demonstrates the value and investment opportu-

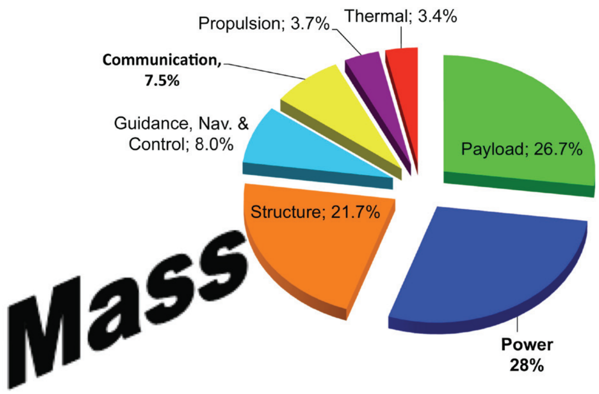

Figure 1. *Spacecraft System Mass Fractions*

nities for improving power system mass, capability, durability in the space environment, lifetime, and cost. Realistic goals for future power and energy storage technology development are a fourfold reduction in system mass and volume, safely lasting over 30 years without replacement, and being capable of operating in a vacuum in extreme temperatures and radiation fields.

The three major subsystems—power generation/energy conversion, energy storage—and power management and distribution (PMAD) each contribute approximately one-third of the mass of the total power system, so all are important targets for mass reduction. Another top technical challenge is the wide variety of power needs for aeronautical and space missions. Depending on the power levels and the duration of use, the power system of choice will vary (Figure 2)—thus requiring a complex suite of technology to be developed to support NASA's wide ranging needs. Power systems that provide the needed mass and

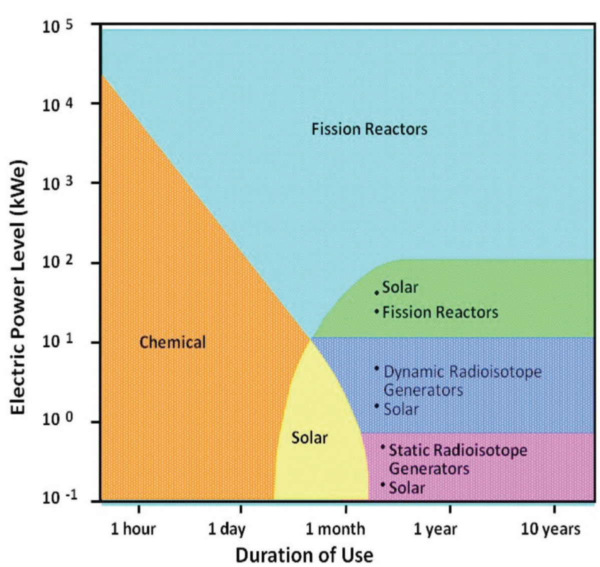

Figure 2. *Power System Characteristics Based on Mission Need*

volume savings (3-4 x SOP) have the challenge of developing components such as high voltage, high power and high specific power solar arrays (1000 V; >100 kW; > 1000 W/kg), high specific energy batteries (500 Wh/kg), high specific power fuel cells (400 W/kg) and power management and distribution systems with high voltage (100-1000 V) high power (100 kW–5 MW)—all across the wide range of needs shown in Figure 2. For example, another top challenge is the need to develop nuclear fission power systems in three power ranges: 2 kW_e; 40 kW_e; and > 1 MW_e with a low specific mass less than 5 kg/kW for the highest power system; these likely require very different approaches. Also, developing and demonstrating a revolutionary system (aneutronic fusion) (>50 MW_e) is a major challenge.

All of these power systems will need to survive and be operational in extreme space environments such as extreme temperatures (-180 to 450°C), dust-laden and high radiation environments (5 MRAD), with high reliability and safety and last from 10- 30 years.

Nonetheless, missions that have not even been conceived will be enabled by high risk/high payoff investments in the development of these power and energy storage technologies. Steady investments will pay off in huge benefits for both NASA missions and national needs.

2. DETAILED PORTFOLIO DISCUSSION

2.1. Summary Description and TA Breakdown Structure

The Technology Area Breakdown Structure for Space Power and Energy Systems is shown in Figure 3.

2.2. Description of TABS Elements

2.2.1. Power Generation

As shown in Figure 3, this element is made up of all the methods of generating power from chemical, solar and nuclear sources, as well as energy conversion and harvesting technology.

2.2.1.1. Energy Harvesting

Energy harvesting is also known as power harvesting or energy scavenging and defined as obtaining power from sources that are available or used for other purposes.

Currently there are some devices being developed for energy harvesting in industry—such as using the waste heat from nuclear plants and steel mills, but not yet used widely for aerospace appli-

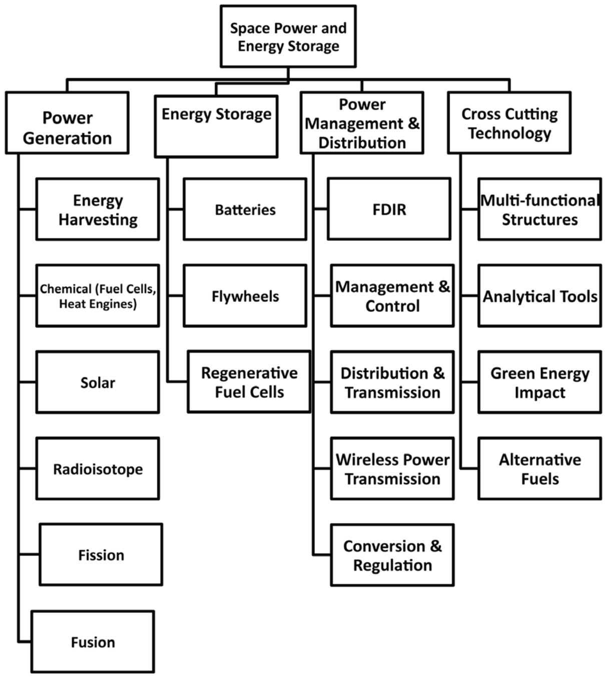

Figure 3. *Technology Area Breakdown Structure for Space Power and Energy Storage*

cations. Nonetheless, there is potential for "push" technologies such as: power from such sources as waste engine heat, warm soil or liquids, kinetic motion, and piezoelectric materials. These novel energy sources can provide local power to improve efficiency, or even provide power to NASA's equipment where other power sources could not operate or would be too large or bulky or inefficient. In order to identify beneficial aerospace applications, studies should be done to identify all promising energy sources such as kinetic energy/momentum, solar (e.g., Lunar waddis), nuclear (radioisotope/fission/fusion), in-space fuel recovery (e.g., ^{238}Pu, He_3, ^{235}U), or local radiation (e.g., Around Jupiter, etc.). Also, various energy conversion methodologies need to be studied, such as piezoelectric, thermoelectric, Stirling, Brayton, Rankine, and nuclear fuel processing. Applications that can benefit from these power systems should also be identified, e.g., enabling power for remote sensors and controls in spacecraft, aircraft engines, and other locations where power was previously not available. Simply put, the challenge for energy harvesting systems is to prove that there is enough power to be gained from these "secondary" systems, and/or to prove that this is an enabling technology to produce power for a novel application, to make it worthwhile.

Energy conversion technology development can enable energy harvesting. NASA's ETDP/ETDD program is currently funding development of Stirling convertors to improve specific power, reliability, and life. These devices are very efficient and can make electricity from "waste" heat from other systems, at efficiencies above 60% of Carnot. Government agencies and private industry are investing significant resources in fuel cell, Stirling convertor, and microturboalternator technologies which are energy conversion methods that can be used to harvest unused energy resources. High power systems (> 100 kW_e) may require development of additional energy conversion technologies, such as organic Rankine or supercritical CO_2 Brayton. In these cases, however, the commercial emphasis on minimizing recurring cost results in technologies and design solutions that rarely support NASA's requirements. Nonetheless, a NASA effort in this field could be quite synergistic with the nation's desire to identify novel new energy systems. Industry is also seeking to be more energy efficient with their manufacturing processes and energy harvesting is one focus area. Another concept for energy harvesting is the retrieval of spent in-space resources for re-use, taking advantage of the energy that was invested in them during launch. Possibly a space processing facility could be established to re-cycle these materials.

2.2.1.2. Chemical Power Generation

Power derived from chemical reactants is widely used in today's rockets. For example, chemical power supports thrust vector actuation for heavy lift capability and in-space power for spacecraft and surface systems with power requirements in the 3-30 kW range. Chemical power systems currently in use for thrust vector control are exemplified by the hydrazine-fired gas turbines used in the Space Shuttle systems, the hydrazine being kept in unique storage. Issues with ground test for these systems have motivated research into electromechanical actuation for launch vehicle applications, and, while Paschen corona issues remain a risk, development of electromechanical actuation will likely supplant that of chemical-powered hydraulic actuation for the foreseeable future. Chemical power systems currently in use for in-space power are exemplified by the Space Shuttle's alkaline hydrogen/oxygen fuel cells. Opportunities for improved life and specific power for this application have motivated an on-going development program in hydrogen/oxygen PEM fuel cells. Bi-propellant turboalternators have also been developed to TRL 3 for similar applications.

Fuel cells have been used to provide power for human exploration missions such as Gemini, Apollo, and Space Shuttle. Fuel cells required for space applications are considerably different than terrestrial fuel cells. Space fuel cells developed to date operate on pure hydrogen (fuel) and pure oxygen (oxidant), while terrestrial fuel cells operate on hydrogen from reformate and air. Space fuel cells also have to operate in microgravity. Further, spacecraft fuel cell technology development is focused on maximizing efficiency (which translates into specific energy), while terrestrial fuel cell technology development is focused on minimizing recurring manufacturing cost. An early version of a Proton Exchange Membrane (PEM) fuel cell was used in Gemini missions (1962-1968). Alkaline fuel cells were used in the Apollo flights (1966-1978) and have been used in the Space Shuttle (1981- present) missions. Alkaline fuel cells have limited life capabilities (< 5000 hours) and low specific power (~49 W/kg). Further they are bulky, require frequent maintenance, and can only operate on extremely pure hydrogen and oxygen. Future human exploration and aeronautics missions require fuel cells with more robust capabilities. Some of the future human exploration vehicles that may require advanced fuel cells include: crew exploration vehicles, large rovers for human surface missions, and astronaut mobility power system. Future aeronautic missions, on the other hand, require green power systems with high efficiency and low manufacturing cost. Fuel cell capability requirements vary from mission to mission. Some of the common spacecraft requirements are: high specific power (200-400 W/kg), long life capability (> 10,000 hours), and high efficiency (~80%). NASA's ETDP/ETDD program is currently funding development of PEM fuel cells and Stirling convertors with improved specific power, reliability, and life potential , but funding limits may only allow this effort to develop this technology to TRL 4/5. NASA is not currently funding development in heat engine conversion cycles other than Stirling. Aerospace contractors have conducted some IR&D on small, bi-propellant Brayton gas turbines. While NASA collaborates appropriately with commercial industry at the fundamental level, this does not often occur at the subsystem level. Opportunities exist that could push fuel cell mission capability. These opportunities include the development of highly reliable systems with passive reactant management and power generation systems capable of drawing reactants from propulsion storage (thereby improving the total propulsion/power specific energy). Balance-of-plant components (regulators, valves, circulation pumps) are the source of most failure modes in fuel cell power plants of any chemistry. Stack bipolar plate designs/materials drive system mass. Catalyst/membrane materials drive system efficiency and durability. High temperature fuel cells (e.g., solid oxide) in particular have durability weaknesses when exposed to rapid load changes. All of these issues must be addressed at an integrated subsystem level in order to meet application challenges.

Reliability can be improved by developing materials and stack designs that manage reactants and water entirely by passive methods (e.g., wicking), thus eliminating most failure modes. Optimized catalysts and membrane electrode assemblies that meet efficiency and durability goals could enable PEM fuel cells to achieve specific power of up to 140 W/kg. Advanced polymer alkaline electrolyte membrane fuel cells and high temperature PEM fuel cells could also offer paths to achieve durability and specific power goals. For fuel cells, nanotechnology offers electrodes with massively increased effective surface area and membranes with higher strength and lower ohmic resistance. In the limit, this can have the effect of eliminating ohmic losses on the cell polarization curve. In the case of the PEM fuel cells, this could increase specific power beyond 400 W/kg. However, it should be noted that, in most spacecraft fuel cell applications, the mass of reactant storage dominates. Thus, even an increase in specific power from the Shuttle fuel cell's 30 W/kg to a nano-engineered cell's 400 W/kg, only raises specific energy from 1.5 kWh/kg to 1.6 kWh/kg.

Development and test of solid oxide fuel cell and Stirling/microturbine designs optimized to NASA specific power/energy and durability requirements are required for full demonstration. These designs will likely require more expensive materials (e.g., platinum interconnects in solid oxide fuel cells) than those being considered for commercial applications. The difficulties involved in managing liquid hydrogen feed in microgravity make it unlikely that chemical power systems can be fed from fuel storage common with a hydrogen/oxygen propulsion system while in space. However, liquid methane can be managed in microgravity. Power can effectively be produced from liquid methane/oxygen propulsion storage via high temperature (e.g., solid oxide) fuel cells, bipropellant turbine or Stirling engines, or a combination. Further, high temperature solid oxide fuel cells enable heat rejection systems that a greatly reduced in mass. Fortunate-

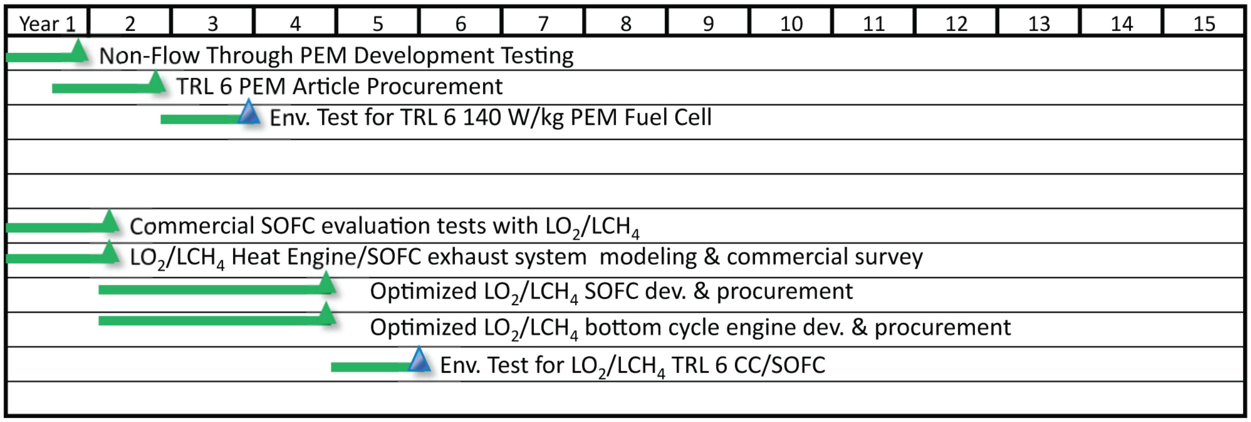

Figure 4. *Chemical Systems and Fuel Cell Technology Roadmap (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

ly, there are potential synergies with other government programs, which are developing fuel cell and heat engine technology with similar requirements and have a standing vendor team.

2.2.1.3. Solar Power Generation

Solar photovoltaic systems have been used to power most of the space science and human exploration (space station) missions launched to date. The space science missions that have employed PV power systems include: Earth orbital, Mars orbital, asteroid fly-bys, lunar orbital, electric propulsion, Mars surface and lunar surface missions. The vast majority of space missions now use multi-junction solar cells (> 29% efficiency) and occasionally use silicon (> 15% efficiency) cells for low cost, unique applications. Body-mounted, rigid panel (approx 60 W/kg) and flexible deployable solar arrays (approx 100 W/kg) are currently being used in spacecraft – dependent on mission requirements and array technology. These state-of-practice (SOP) solar power PV power systems are mostly suitable for low to medium power (0.5-30 kW) applications. Further they have potentially degraded performance at high temperatures (above 140°C) and low intensity/low temperature space environments found beyond Mars orbit. Future space science and human exploration missions require solar power PV systems with significantly higher performance capabilities compared to SOP systems. The capabilities needed vary significantly from mission to mission. Some of the critical requirements of the future space missions are: 1) high voltage and high power arrays (300-1000 V, > 100 kW) with high specific power arrays (500-1000 W/kg) capability are needed for high power electric propulsion missions; 2) dust-tolerant PV arrays with high specific power and high efficiency are needed for human and robotic surface missions; 3) PV systems with low intensity/low temperature (LILT) and high radiation tolerant (5 Mrad) capabilities are required for outer planetary missions (> 3 AU); 4) Large arrays which are structurally and dynamically durable under deployed conditions, while retaining stowed volume during launch; 5) High temperature solar cells and arrays (> 200°C) are required for inner planetary missions; and 6) crew exploration vehicles will also require high specific power arrays. As illustrated in Figure 5 NASA applications have much broader environmental requirements and NASA/other agency/commercial PV common interests are only in LEO and below, where other agencies are investing in the development of high specific power arrays and in low cost cells and arrays for terrestrial applications. Unfortunately, despite significant need, and major challenges, no significant NASA investment is presently planned to address the challenges displayed in the other regions of the solar system in Figure 5, leaving a gap when addressing NASA needs. Therefore, a new program needs to be established that emphasizes the development of high efficiency cells, cells that can effectively operate in LILT conditions (> 3 AU), cells and arrays that can operate for long periods at high temperatures (>200°C), high specific power arrays (500-1000 W/kg), electrostatically-clean, radiation tolerant, dust tolerant, and durable, re-stowable/re-deployable arrays. For large space power systems, ground testing and verification methods need to be developed. Cost will be a major driver for large PV power systems. Cost reduction can be addressed through reducing cell cost, modularity of solar cell panels, improved manufacturability, and reparability.

2.2.1.4. Radioisotope

Radioisotope power systems (RPS's) based on

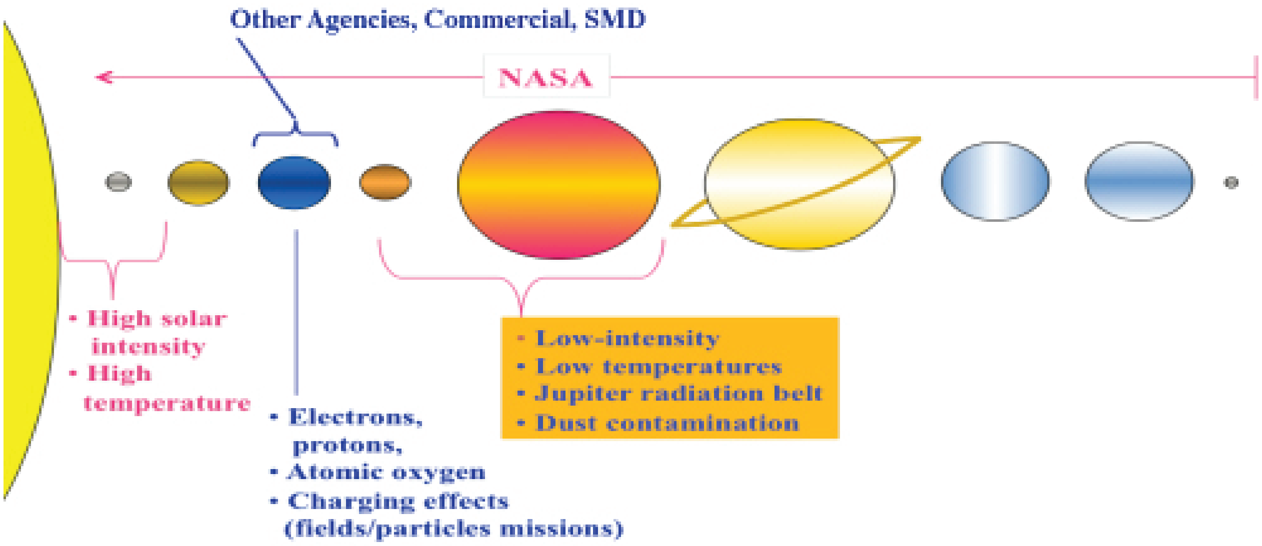

Figure 5. *Other Agencies, Commercial Space and NASA Mission Synergies (Overlaps and potential synergies across current and planned investments)*

plutonium-238 and thermoelectric converters have been used in space since 1961, with a typical performance of 3-5 We/kg, 6% efficiency, and over 30 yr (demonstrated) life. RPS's operate independent of solar proximity or orientation. In addition to enabling sophisticated science missions (e.g. Pioneer, Viking, Galileo, Ulysses, Cassini, New Horizons) throughout the solar system, RPS's were used on Apollo missions 12-17 and the Viking landers.

Looking forward, RPS's in the 0.1 – 1000 We power range could continue to enable exciting science missions, and could also be useful in supporting human exploration missions. High specific power RPS's could enable radioisotope electric propulsion for deep space missions, enhancing or enabling numerous NASA missions of interest Specifically, there are three types of radioisotope power systems that need to be developed: 1) advanced radioisotope thermoelectric generators (10-15 W/kg, 15-20% efficiency, 15 year life); 2) advanced Stirling radioisotope generator (ASRG) (10-15 W/kg, 35% efficiency, 15 year life); and 3) small (1-10W) RPS's that can survive a 5000-g impact, including both the heat source and power conversion system. The radioisotope of choice is plutonium-238, which has excellent power density and lifetime, and minimal radiation emissions. The use of a more readily available isotope (e.g., ^{241}Am) instead of ^{238}Pu would result in a performance penalty for most RPS missions and would require an extensive qualification effort. However, the use of alternative isotopes (in addition to ^{238}Pu) could potentially allow higher power (>1 kWe) radioisotope systems to be developed and utilized, and allow more extensive use of radioisotope systems. NASA's Science Mission Directorate is continuing to develop advanced radioisotope power systems for future space science missions. The ASRG is making excellent progress towards the goals of efficiency greater than 28%, specific power of 6-8 We/kg, and life exceeding

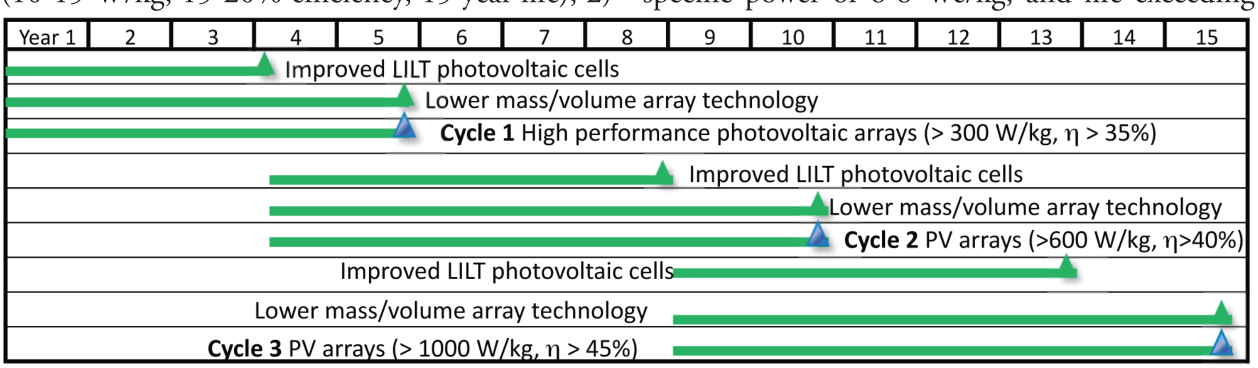

Figure 6. *Photovoltaic Systems Technology Roadmap (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

14 years.

The major challenges for RPS's are: (1) to create high efficiency power conversion systems with very long life capability, (2) the severe impending shortage of ^{238}Pu, which is no longer being produced in the U.S. (if the ^{238}Pu availability issue is not resolved, there is a need to develop and qualify alternative nuclear heat sources); and (3) to invent RPS's which can survive a 5000-g impact. Foremost is the need for a new program to establish U.S. plutonium-238 production facilities, or the development and production of alternative nuclear heat sources. NASA is working with other government agencies to implement this new program. Flight validation of the ASRG and other radioisotope power systems is very important to ensure the acceptability of these systems on future missions. This new program must also focus on developing small, impact-resistant radioisotope power systems and life-prediction models and experimental testing techniques. Advanced RPS's could be used on Discovery, Flagship, and Flexible Path precursor missions .

2.2.1.5. Fission

Fission provides "game-changing" solutions for powering advanced NASA missions. Game-changing attributes of space fission systems include virtually unlimited fuel energy density, the ability to operate independent of solar proximity or orientation, and the ability to design for operation in extremely hostile environments (e.g., high dust, high radiation, or high temperature). Fission can enable a power-rich environment anywhere in the solar system. Fission systems can support science missions in the 0.5-5 kW_e power range where ^{238}Pu supply issues may preclude use of radioisotope systems. Workhorse 10 – 100 kW_e fission systems can support surface and robotic missions. High power fission systems (MW-class) are required for nuclear electric propulsion missions – potentially including crewed missions to Mars, and other destinations. Fission reactors flown in space by the U.S. and the former Soviet Union between 1965 and 1987 operated at coolant outlet temperatures and thermal powers comparable to those required by a 21^{st} century 40 kW_e system. Space reactor programs not resulting in flight succeeded in developing high temperature / high performance fuels, materials, and heat transport systems. The experience gained from nearly 7 decades of terrestrial fission systems can benefit the design and development of future space fission systems. Fuel and materials technologies from terrestrial systems (e.g., FFTF fast fission test facility and EBR-II experimental breeder reactor) are applicable, especially for first generation space fission systems such as those being developed under ETDD. High uranium density fuels developed for research and test reactors could also be of use for ultra-compact systems. NASA ETDD's ongoing space fission power project involves a close partnership between NASA and other external organizations. The partnerships are working extremely well, with significant progress being made towards ground-testing a ¼ -scale technology demonstration unit (TDU) by 2013. Components for the

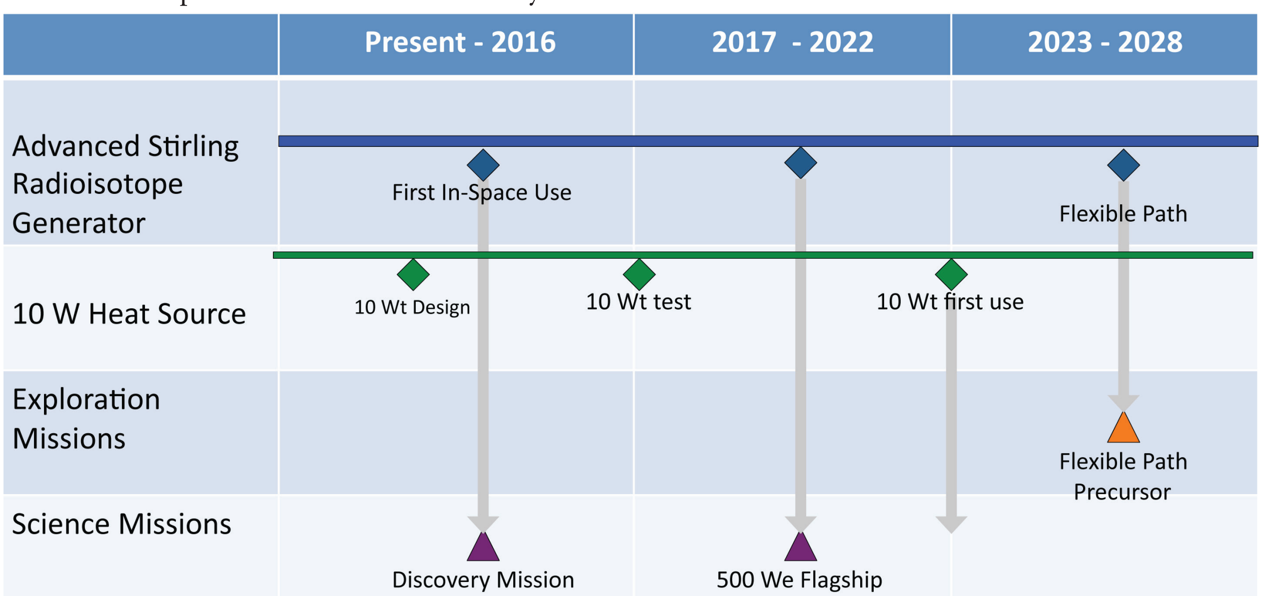

Figure 7. *Radioisotope Systems Technology Roadmap (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

TDU have been designed, fabricated, and tested. Fabrication of the integrated TDU is scheduled to begin in FY11. Development and operation of the TDU will provide an excellent foundation for all future space fission power and propulsion work, from both an organizational and hardware standpoint. The current program is focused on a 40 kW_e space fission power system with emphasis on safety, reliability and affordability. The system utilizes reactor and other technologies with significant terrestrial heritage. For potential 0.5-5 kW_e fission systems, a GRC-led study was completed in 2010. The study utilized the NASA team that has been established for the 40 kW_e ETDD project. The 0.5 – 5 kW_e systems would also take advantage of ongoing research at NASA (power conversion, radiators).

The top technical challenges for fission systems are application specific. A 0.5-5 kW_e fission system would require high uranium density fuel; simple, lightweight core-to-power conversion heat transfer; low mass power conversion (at low power); and design for safety, reliability, and minimum mass. Existing (or near term) materials, fuels, power conversion and waste-heat rejection technologies could be used. Simply put, the technologies exist for developing near-term, mission-enabling space fission systems. The major challenge for these initial systems is integrating the technologies into a safe, reliable, affordable system. For second generation space fission systems (and beyond), the major challenge is developing technologies to even further improve performance. Specific technologies include high temperature reactor fuels and materials, high temperature / high efficiency power conversion, and light-weight, high temperature radiators. For example at high power levels (> 100 kW_e), space fission power system performance would benefit from advanced fuels, advanced power conversion, and light-weight radiator technologies. Innovative reactor designs would also improve performance. Specific technologies could include development of high-temperature (~1800 K) cermet fuels (e.g.,W-UN) and of liquid or vapor core fission reactors (e.g., UF_4) capable of operating at temperatures above 2500 K. Advanced power conversion options could include alkali metal Rankine cycles (building on work performed in the 1960s) and Magnetohydrodynamic (MHD) power conversion. Light-weight radiators capable of operating at temperatures above 1000 K could also benefit integrated system performance.

Next generation systems can be developed to TRL 6 via a combination of nuclear testing in collaboration with the other government agencies and fully integrated non-nuclear testing at operational government facilities. Improved conversion cycles, heat transfer systems, and radiators can all be developed by NASA and tested to TRL 6. Nuclear testing will be performed as required for advanced fuels, components, and reactors. Realistic, integrated system testing will be used to demonstrate advanced fission systems at TRL 6.

2.2.1.6. Fusion

Fusion power for electric propulsion could support human missions to Mars with round-trip

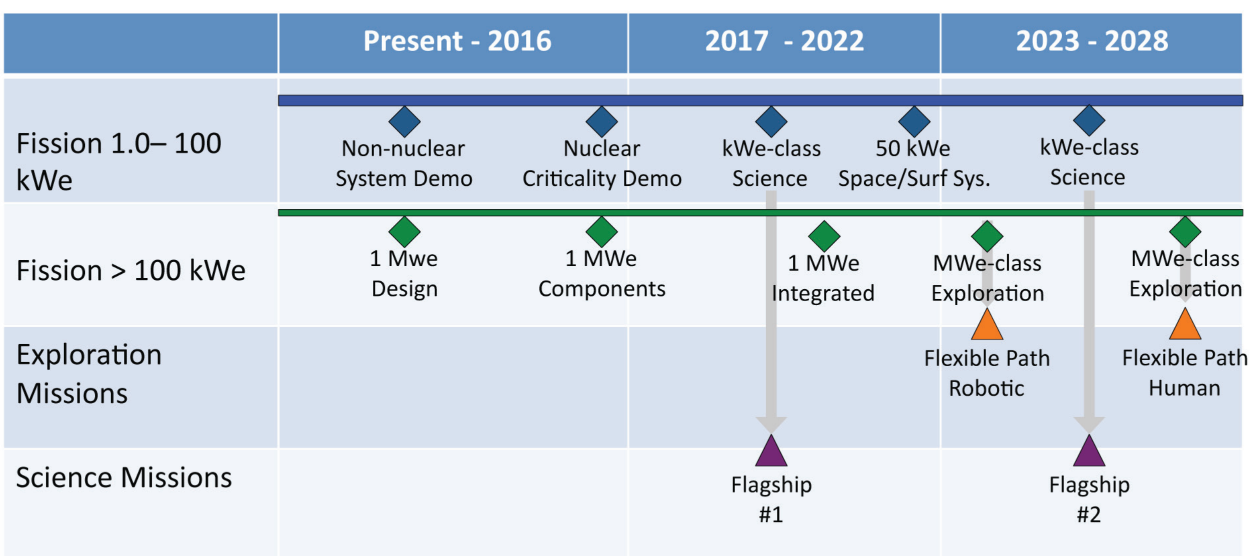

Figure 8. *Fission Power Systems Technology Roadmap (Time-phased roadmap (graphic) of activities necessary to mature fission technologies)*

times under one year and large, high power robotic missions throughout the solar system. Such missions start to be enabled by power/propulsion systems in the 50+ MW range with total specific masses (αT) less than 2.0 kg/kW. Within the constraints of current (and foreseeable future) fusion technology, these values of αT can only be achieved via low-neutron or neutron-free (aneutronic) fusion reactors. If an electric propulsion system can be developed with $\alpha < 1.0$, efficiency (η) > 0.6 and PMAD with $\alpha < 0.5$ and $\eta > 0.9$, delivering $\alpha T < 2.0$ kg/kW would require a fusion reactor/power conversion system with $\alpha < 0.5$ kg/kW and $\eta_{conv} > 0.8$. Due to the high specific mass of heat-based neutron-to-electric power conversion systems, to the residual radiation from neutron activation, and to the need of neutron shielding for critical components and crew, delivering this capability requires development of fully aneutronic fusion power generation.

Fusion power is considered to be most readily attainable through heating and confinement of a D-T plasma until the condition at which the plasma can heat itself (ignition) is reached. The D-T reaction releases most (80%) of its energy in the form of neutrons, so a D-T fusion reactor requires heavy shielding and heat-based energy conversion to produce electricity. Since the 1960's fusion research has focused on the D-T reaction, as it appears to be the least challenging from the perspective of plasma confinement and reactor technology for utility grid power generation. Steady progress towards the goal of net fusion power generation continues to be made, with most of the investments devoted to the magnetic plasma confinement approach. The primary effort currently underway is the ITER "Tokomak", a very large magnetic confinement device, which is projected to lead to net power generation in the 2030's with $\alpha > 200$ kg/kW at $\eta_{conv} < 0.4$ and 10 GW.

The aneutronic fusion reaction p-^{11}B release their energy primarily in the form of charged alpha particles and thus enable direct conversion methods that are, in principle, much more efficient than any heat engine conversion. Also, if no neutrons are emitted, little shielding and no radioactive material handling facilities are required (that are instead necessary for fission or D-T fusion reactors). This would reduce the flight development cost of an aneutronic fusion reactor to well below that of even a fission power system. Aneutronic reactions thus have high potential for low-α space power generation. However, the high ion energy that is required to reach the peak fusion cross section of the p-^{11}B reaction is considered unobtainable with the various thermal plasma confinement methods that are being pursued for terrestrial fusion power reactors. Thus, development of such reactors has not been aggressively pursued. The engineering of direct conversion of fusion product into electricity (for example the Traveling Wave Direct Energy Conversion, TWDEC, and the Periodic Focusing Direct Energy Conversion systems) has progressed to TRL 3/4 in laboratory experiments. The technology for using directly the energy from an aneutronic fusion reactor to create plasma for thruster propellant (to be then exhausted through a magnetic nozzle) is at a similarly low TRL level.

As noted above, no significant amount of funding is directed toward engineering for aneutronic fusion of potential use in NASA missions. Funding of research for related direct energy conversion systems remains almost zero. Whatever the investment, the primary technical challenge in aneutronic fusion remains the demonstration of stable confinement of plasmas with ions of sufficient energy to produce high energy yield. With presently known magnetic confinement configurations, thermal plasmas of sufficient energy to sustain these reactions cannot be confined for a sufficient time. Thus, sustaining beam-collider plasmas appears a more viable solution, yet these have many unknowns. Other challenges include the development of systems for direct conversion of high-energy alpha particles produced in the fusion reactions. It should also be noted that a propulsion/power system with $\alpha T < 1.0$ kg/kW is realistically possible only if a thrust-producing propellant

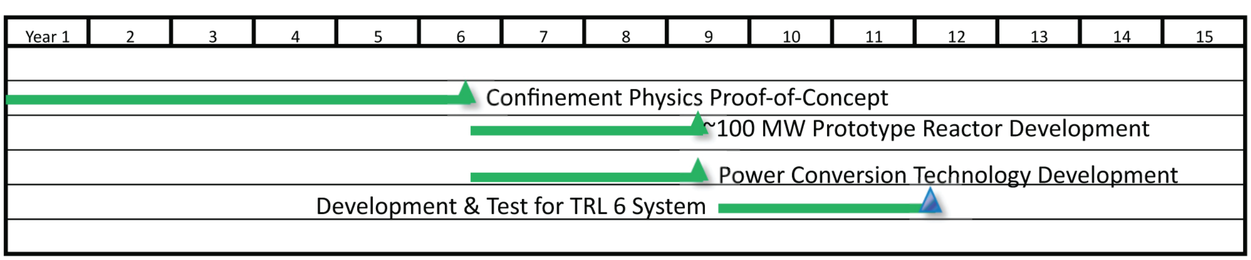

Figure 9. *Fusion Power System Technology Roadmap (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

jet can be generated from the energy of the fusion products of the reactor.

2.2.2. Energy Storage

This element is made up of all the methods of storing energy after it has been generated from solar, chemical and nuclear sources if the energy is not needed immediately.

2.2.2.1. Batteries

Batteries are used in space missions for a wide variety of applications. Primary batteries (single discharge batteries) are used in missions that require one-time use of electrical power for few minutes to several hours. Primary batteries have been used in planetary probes and sample return capsules (Stardust, Genesis, Deep Impact, and Galileo), Mars Landers (MER), and Mars Rovers (Sojourner). Rechargeable batteries (secondary batteries) have been used mainly for load-leveling and for providing electrical power for survival during eclipse periods on solar powered missions and as the source of power extravehicular activity suits. They have been used in orbital missions (TOPEX, Mars Global Surveyor, and Mars Reconnaissance Observer) as well as Mars Landers (Mars Pathfinder) and Mars Rovers (Spirit and Opportunity). State of practice primary and rechargeable batteries are heavy, bulky and have limited capability to function in extreme space environments such as high and low temperatures and radiation. Safety concerns exist with some of the primary lithium and rechargeable Li-Ion batteries. A summary of the characteristics of the state of practice primary and rechargeable batteries are given in Table 1:

Advanced batteries are required for a number of future ESMD, SMD, SOMD, and ARMD missions. The ESMD missions include astronaut equipment and EVA suits, crew exploration vehicles, in-space habitats, surface habitats, humanoid robots, landers, and ISRU. SMD missions include planetary probes, landers, rovers, orbiters (GEO, LEO, HEO, and planetary). SOMD requires batteries for ISS astronaut equipment, life support systems, and as the energy storage element of a photovoltaic based power system, this includes replacements for the existing Ni-H2 batteries with advanced technology. ARMD requires high specific energy batteries for aviation energy storage in hybrid and more-electric aircraft.

Advanced batteries with 2-3 X performance capability compared to the state of the practice batteries are required for a number of future NASA space missions listed above. These advanced batteries will provide significant mass and volume savings and operational flexibility. The requirements will vary from mission to mission and the driving requirements for some critical missions are: 1) Astronaut /EVA equipment require high specific energy rechargeable batteries (500 Wh/kg, 1000 cycles); 2) Human habitat power systems will benefit significantly from batteries with large storage capability (~MWh, 5000 cycles) and high specific energy (500 Wh/kg); 3) Human/robotic landers and rovers require high specific energy (500 Wh/kg, 5000 cycles) and ultra low temperature rechargeable batteries (-100°C); 4) Crew exploration/rescue vehicles require high specific energy batteries (> 500 Wh/kg); 5) Planetary probes require high specific energy primary batteries (1000 Wh/kg) with low temperature operational capability (-160°C); 6) Inner planetary missions require high temperature (450°C) primary and rechargeable batteries; 7) Earth/planetary orbiters require long life (> 20 years, 100,000 cycles) and high specific energy rechargeable batteries (300 Wh/kg); 8) Heavy lift launch vehicles require high specific energy primary batteries (1000 Wh/kg) and high rate capability (3 kW/kg). The major technical challenges to develop these advanced space batteries include: 1) development of high specific capacity cathode nano-materials (500 mA-hr/gm); 2) high specific capacity anode nano-materials (>1000 mA-hr/

Table 1. *Current state-of-the-art/practice for primary and rechargeable batteries*

SOP System	Technology	Mission	Specific Energy, (Wh/kg)	Energy Density, (Wh/l)	Operating Temp. Range, (°C)	Cycle Life	Mission Life (yrs)	Issues
Primary Batteries	Ag-Zn, $Li\text{-}SO_2$, $Li\text{-}SOCl_2$	Delta Launch Vehicles, Cassini Probe, MER Lander, Sojourner Rover	90-250	130-500	-20 to 60	1	1-9	• Limited operating temp range, • Voltage delay
Rechargeable Batteries	Ni-Cd, $Ni\text{-}H_2$	TOPEX, HST, Space Station	24-35	10-80	-5 to 30	> 50,000, @25% DOD	>10	• Heavy and bulky, • Limited operating temp range
Advanced Rechargeable Batteries	Li-Ion	MER: Spirit & Opportunity Rovers	100	250	-20-30	> 400 @50% DOD	>2	Cycle Life

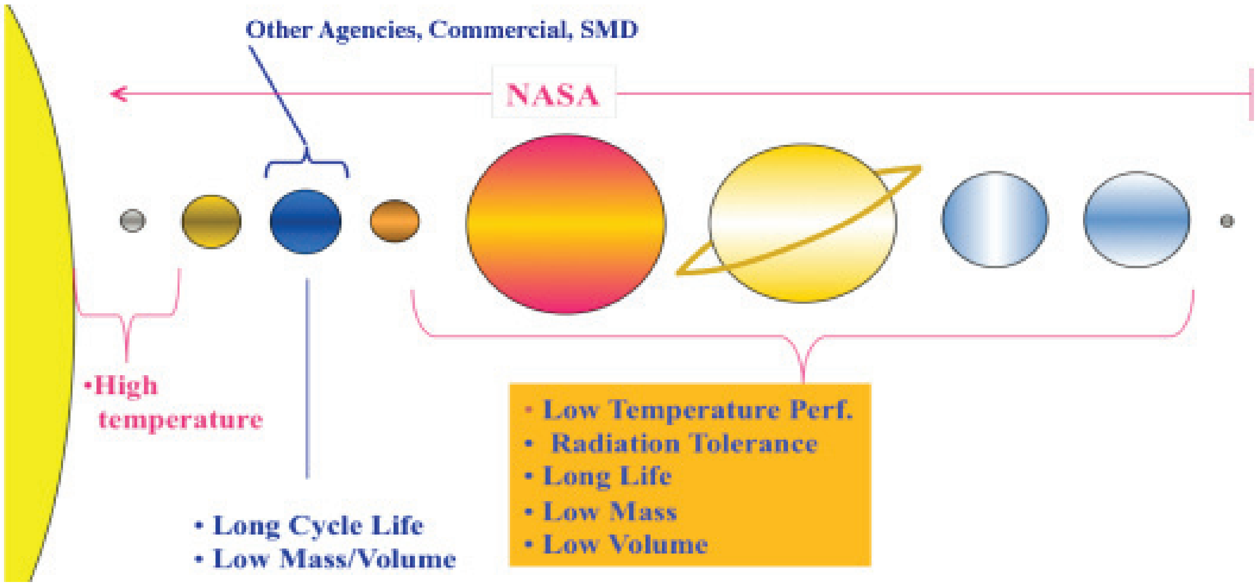

Figure 10. *Battery Development Synergies between NASA and Commercial Space. (Overlaps and potential synergies across current and planned investments)*

gm); 3) high voltage (>5V), highly conducting electrolytes; 4) overcharge protection additives and safety concepts and devices; 5) multi-functional battery structures; 6) extreme temperature and radiation-resistant electrolytes and electrodes; 7) green battery materials and processes; and 8) development of advanced electronics to implement optimized charge methodologies to enhance life and safety is also required.

As seen in Figure 10, NASA's energy storage needs span a greater range of environments and cycle requirements than other organization's applications. NASA's ETDP/ETDD program is presently investing ~$2-3M/ year to develop rechargeable Li-Ion batteries of 165-260 Wh/kg. This current NASA ETDDP program is focused on meeting the near term ESMD needs. It does not address the future SMD, SOMD and ARMD needs. Other government agencies are investing several tens of millions of dollars per year in the development of low cost batteries for terrestrial electric vehicle (150-200 Wh/kg) applications, but its focus is on low recurring cost and not highest possible performance. To augment the current investment, a new program is needed to develop advanced primary and rechargeable batteries required for future SMD, ESMD, SOMD and ARMD missions.

2.2.2.2. Flywheels

Flywheels offer space craft a novel system for combining attitude control (replacing momentum wheels) and energy storage (replacing batteries) which reduces the overall mass of the combined systems. Flywheels have the advantage of being able to quickly deliver their energy, and can be fully discharged repeatedly without harming the system, and have the lowest self-discharge rate of any electrical energy storage medium. They have potential to be the best possible storage media per unit mass (2700 Wh/kg theoretically) with

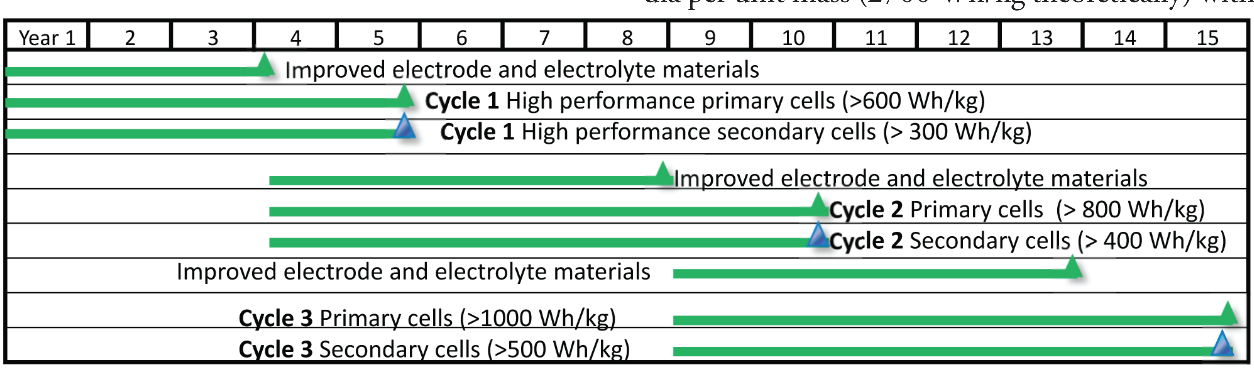

Figure 11. *Battery Technology Roadmap. (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

the application of nanotechnology. For example, the development of carbon nano fibers which can be wound to form ultra strong, lightweight rotors would enable higher energy storage capability for flywheels. These rotors will also be much safer, requiring lighter weight shroud material. Bearing technology development such as superconducting magnetic bearings and advanced generators would also advance flywheel technology.

During the last 10 years, NASA's research and technology efforts created engineering model units which were fabricated and tested (25-30 Wh/kg) to be able to replace the batteries on the ISS. Ground demonstrations were very successful and a prototype system was readied for potential installment on the ISS. Nonetheless, today, there is no planned NASA funding for flywheels. At the same time, there is increasing military, industrial and commercial terrestrial power grid storage interest.

The major challenges are to advance flywheel technology to achieve the potential to store energy for kWh & MWh systems at a specific energy of up to 2700 Wh/kg with carbon nano fiber rotors (as mentioned above) and to attain a charge life of greater than 50,000 cycles and lifetime of greater than 20 years with high reliability and safety. To meet these challenges, NASA could pursue flywheel component miniaturization, nanotechnology-based rotors, magnetic bearings, reliability, and system development and demonstration.

2.2.2.3. Regenerative Fuel Cell Energy Storage

Regenerative fuel cell systems (RFCs) are attractive for space missions that require large scale energy storage of the order of several MWh. This is especially important for large-scale energy storage applications such as space habitats and planetary surface systems requiring 10's of kW electrical power. Unlike batteries which become very large when designed to address long periods of operation, regenerative fuel cells only require larger storage containers and additional reactants to extend their operational period. Regenerative fuel cells required for large scale energy storage applications would be enhanced by high specific energy (Up to 1500 Wh/kg), high charge/discharge efficiency (up to 70%), high reliability, and long life capability (~10,000 hours).

Three RFC chemistries are in development: 1) Polymer Electrolyte Membrane (PEM), 2) Alkaline, and 3) Solid oxide. Among these three chemistries, PEM RFC system is at the most advanced stage of development. The major subsystems of an RFC are: fuel cell, electrolyzer, reactant storage, thermal management, and control. Space RFC systems are considerably different than terrestrial RFC systems. Air-based RFCs (recycling only hydrogen and water) are being developed for commercial terrestrial and military applications. Space RFC systems have no air available and must be designed for operation with oxygen. Furthermore, space RFC systems have to be optimized for multi-gravity environment operations (0g – launch loads) and also for thermal and water management in space thermal vacuum environments. Space-quality RFC technology feasibility demonstrators have been assembled and tested to demonstrate technology viability and determine system operations. Currently PEM RFCs are no further advanced than a TRL of 3-4 and have been demonstrated only in terrestrial experimental test beds at 50 % round trip efficiency and operated at less than 100 cycles.

NASA's ETDD and SBIR programs are currently funding limited development of critical components and devices for hydrogen/oxygen PEM fuel cells and electrolyzers with improved specific power, reliability, and life potential. Both discrete (separate fuel cell and electrolyzer stacks) and unitized (one stack) systems have been examined. The primary focus in technical development to date has been on the fuel cell portion. ETDP plans were to begin addressing electrolysis via SBIR efforts (which has been implemented), then begin to support with project funds in FY11-12 time frame. Despite the termination of RFC funding under ETDD, there is a defined need for advanced space quality electrolysis systems, thus fuel cell and electrolysis work are planned to continue as separate elements. Other government agencies are investing in a similar system in support of energy storage for blimps. Other government agencies and private industry are investing significant resources in PEM fuel cell technologies, but fuel cell design, cathode catalyst, water management and operational conditions are not the same as the oxygen-fed system required for NASA. Commercial emphasis is primarily placed on minimizing cost and in technologies, and design solutions for terrestrial operations rarely support NASA spacecraft requirements.

A new technology program is needed to develop high specific energy, high efficiency, and long life, regenerative fuel cells that are required for the large scale energy storage needs of future ESMD and ARMD missions. This program needs to fo-

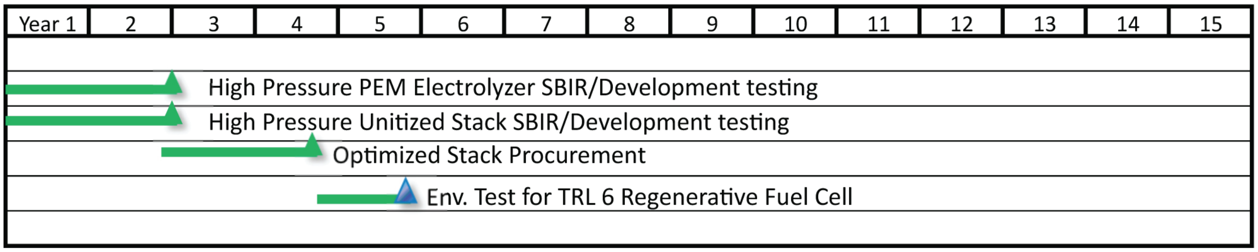

Figure 12. *Regenerative Fuel Cell Systems Technology Roadmap. (Time-phased roadmap (graphic) of activities necessary to mature technologies)*

cus efforts in the following technical areas: 1) trade studies on the selection of most promising RFC chemistries for a specific application (Alkaline, PEM and Solid oxide); 2) development of high efficiency fuel cells and electrolyzers; 3) reactant storage system mass reduction; 4) improved water and thermal management subsystems; 5) design and fabrication of integrated RFC systems; and 6) test and validation. A NASA effort in this field could be quite synergistic with another agency's program, which is developing a similar RFC and is working with an established vendor team. Any PEM and Solid Oxide electrolysis development effort for regenerative fuel cells could be completely in common with that for life support oxygen generation, such as is operating on Space Station, and with ISRU.

2.2.3. Power Management & Distribution (PMAD)

PMAD is the "backbone" that holds a power system together. It is often neglected in discussions of technology development and innovation in favor of the more visible larger power components and is often thought of with a "buy it by the yard" mentality. However technology developed for reducing the mass of the PMAD system would impact one-third of the mass of the whole power system. For the time period from now until 2016, the need is to qualify a range of space-grade high voltage active power semiconductor transistors (comparable to the commercial offering) and passive components and adapt terrestrial advances in power management and control to new space power system architectures. For 2017-2022, the challenge is to improve qualified power semiconductors by increasing the current rating, lowering switching and conduction losses, and increasing junction temperature tolerance. For the period 2023 – 2028 another top challenge would be to develop a viable power beaming approach, as described later in this section.

2.2.3.1. PMAD Overall

Typically, PMAD power density around 5kW/kg is at or just above what can be achieved with custom power converters (in the range of 1kW to 1MW) using the latest commercially available parts. It should be noted that these parts often outperform space grade parts significantly due to the intrinsic "inertia" of class S (space grade) production lines. As such, in general it's very hard for a space based PMAD system to achieve this mark due to poor performance in terms of losses. In addition, although high voltage parts are commercially available above 1000V, the rigor and overhead of tracking and screening that comes with the higher part grades means you can't find similarly rated high voltage parts in any manufacturer's space grade offering. In fact, while commercial grade MOSFETs are available with ratings of at 1200V and 600A (Powerex), no space grade analog exists. As a result, generally electronic component voltage ratings (usually semiconductor device as well as capacitor ratings) limit the system bus voltage. Further these factors are more constraining than the issues arising from cable insulation effectiveness and/or the separation issues (arcing/corona) associated with the higher voltage system. In terms of environmental limitations, silicon based semiconductors junctions often carry a practical limit to junction temperature at or near 150°C which has a direct impact on the level of heating a device can withstand due to its internally generated losses. This also has an impact on radiator size when, for a given internal loss level and junction to case thermal resistance, the temperature sink must be low enough to accommodate the ΔT required to stay beneath the 150°C junction temp with margin. In addition, for a given silicon based device, there is often a tradeoff that exists between breakdown voltage and conduction loss (on state resistance) as well as a trade between switching and conduction losses. These trades collectively present an obstacle to increasing power density. In addition to these aforementioned limitations, capacitors, a key component in the energy balancing function within PMAD conversion steps, typically employ electrolytic variants. Electrolytic Capacitors: Tantalum and Aluminum – Aluminum capacitors are used on ground or pressure controlled areas in space. Tantalum non-solid (MIL-PRF-39006) and tantalum solid capacitors (MIL-PRF-39003) are hermetically sealed and are currently being used in space applications. However, they often carry limited operating temperature range and present poor density. In terms of external pressure: Aluminum electrolytic capacitors can operate up to 80,000 feet and pressures as low as 3 kPa. Exceeding these limits can damage capacitor. Temperature ratings: In addition, since temperature is one of the main factors in capacitor life, temperature ratings need to be increased. For example, tantalum capacitors (MIL-PRF-39006) currently have an operating temperature between -55°C and 85°C. These capacitors are de-rated when operated between 85°C and 125°C. In many cases super capacitors promise improved capability in a number of these areas but currently carry their own limitations. Super capacitors, also known as Electric Double Layer Capacitor (EDLC), have the highest energy density. Currently in production we find 30Wh/kg which is thousands of times greater than what we achieve with electrolytic capacitors. However, in general, supercaps have low voltage ratings. Cells have to be connected in series to get higher voltages which increases ESR and decreases the reliability.

Across all the areas within PMAD, focus areas for technology push should target improved power density and environmental tolerance. Each of these overarching PMAD focus areas will be addressed first in the paragraphs that follow. In terms of mass, distribution system weight is driven by system cable/buss mass. Since a higher operating voltage can yield a lower (distribution system) weight for the same power level, it is both a near term and a long term goal across all areas of PMAD. For higher PMAD power density, the emphasis must be on improved semiconductor device and passive device characteristics. This would include including a higher operating voltage to enable smaller distribution system mass. In addition, this also drives the need for devices with higher break down voltages as well as reduced switching and conduction losses. In addition to the limitation these active devices impose, passive devices also become limiting factors. Capacitors used today in space applications need to have higher densities, higher operating voltages, and higher temperature tolerance to achieve future space missions.

From an environmental perspective for PMAD overall, the parts in these systems must be better suited to the space environment for both earth-orbiting as well as interplanetary missions while needed performance improvements are simultaneously achieved. In particular, we need semiconductor parts with improved junction temperature operating tolerance and radiation tolerance, possibly via nontraditional semiconductor materials. Further, for EDL systems, power systems and their associated hardware need to be capable of withstanding extremely high g impacts delivered on landing.

2.2.3.2. Wireless Power Transfer

Wireless power transfer can be split into two categories based on transmit power and throw distance. In the smaller class, analogous to rechargeable toothbrushes and cell phone charging pads, electric or magnetic fields are used with a pickup mechanism to charge without electrical contact; these are useful to power small rechargeable batteries such as those used in wireless sensors. In the larger class, commonly referred to as high intensity power beaming, power could be transmitted via laser beam or over microwaves that can be used for launch capabilities to deliver a payload from Earth to LEO, electrically refuel UAVs or geosynchronous satellites, or for numerous deep space applications. Further, power beaming techniques could conceivably have a drastic effect on energy storage mass in the system as strategically placed transmitters could reduce the power system's required on-board energy storage capability. In the case of high intensity power beaming, 50% efficiency has been achieved at the receiver. The final output electrical power density at the receiver has reached 20 W/cm^2, which has been limited primarily by the source and the collimating optics.

2.2.3.3. Distribution & Transmission

Cryogenically cooled conductors, motors, etc. have greatly reduced conduction losses and resultant power densities can be factors greater than those at ambient temperatures, however, the application of cryogenic technology needs to be done on a case by case basis after analyzing the added value against risk and complexity trades.

Another possibility is embedding signal paths in composite structures. An interesting concept, originally proposed by members of the military aircraft community, would embed electrically reconfigurable signal pathways into composite structures. The pathways could be multipurpose delivering low power levels to loads such as sensors, act as communications links, sense spacecraft structural damage, and even reroute signals around damaged structure and any resulting broken pathways.

2.2.3.4. Conversion & Transmission

For conversion, in addition to the overarching issues raised above, building blocks, commonly known as Power Electronics Building Blocks (PEBB), that are modular and scalable need to be developed. These modules should be able to be reapplied to new designs and scaled for appropriate voltages/power levels with minimal recurring analysis and as such have a high level of reusability.

2.2.3.5. Fault Detection, Isolation, and Recovery (FDIR)

For FDIR, a common, highly capable/configurable semiconductor-based protection and switching design should be developed. Commonly called a Remote Power Controller (RPC), these devices serve as both power control and circuit protection in typical space PMAD systems. The implementation of these devices is often customized from project to project. Within FDIR, an area where we should push technology would be the development of a highly competent, configurable RPC design that implements data bus communications, can operate at high voltage ratings, be low loss and high current capable while implementing a user selectable variety of advanced protection algorithms such as programmable set points, current limit, I^2t, etc. This standard design could be qualified once, be useful in any NASA mission, and reduce overall cost/ weight while improving fault protection and isolation characteristics.

2.2.3.6. Management and Control

In control and management of power, the terrestrial renewable energy boom as well as our nation's interest in a power grid topology termed 'Smart Grid" dovetails into the technology push strategies that NASA should focus on. Smart Grids, with a multitude of interconnected sources and loads require advanced power flow control algorithms that promise more efficient more reliable power system operations. These same concepts can and should be developed into space power systems. In addition, power system control algorithms need to be highly reliable but also be resilient when faults do occur to enable the long term autonomous operation that interplanetary space systems or surface power systems would need much in the same way terrestrial smart grid technologies are advancing.

2.2.3.7. Major Challenges

Major challenges to the development of high power, high voltage PMAD are directly related to part capability and availability and limited expertise in high voltage design. To elaborate, high power systems require higher distribution voltages. This means both power semiconductors as well as passive components at this voltage rating need to be developed that enable the higher bus voltage. These parts are not commercially available at this time. In addition to the voltage and current rating of these power semiconductor parts, improved junction temperature tolerance, radiation tolerance coupled with reduced switching and conduction losses must be developed to accomplish the mission. While these issues are being partially addressed through commercial development efforts, military and space grade parts are not seeing this same level of innovation due to a variety of factors related to supply and demand on the worldwide commercial market. In addition, NASA and its partners lack the expertise needed in high voltage design at this power level. NASA's previous work in this area was limited to high voltage, low power sources for instrument development and those knowledgeable in this area are also few and getting fewer.

There are a number of technology pushes within PMAD that NASA will have to champion in order to achieve revolutionary rather than evolutionary advances. NASA will have to augment its current efforts in the R&D of wireless power transfer to include low power magnetic and electrically coupled methods as well as the higher power beaming techniques that employ mediums such as lasers and microwaves in order for these technologies to be useful and game changing. In addition, NASA should invest in the development of beamed power distribution. A new concept for beamed energy involves use of fiberoptic transmission of light power from a laser source. This could revolutionize the way we conduct robotic surface exploration (it is already revolutionizing deep sea exploration). Continued development could enable use of this method of power distribution for a wide range of space and aero applications. This development activity would be in addition to the development of conventional beaming approaches described here via free laser light and microwaves. In terms of power semiconductor development, while we see incremental improvement, this is constrained primarily to the commercial markets. NASA will have to develop the space grade market segment for the commercial suppliers leveraging an increased demand in the commercial market for many of these same attributes (less the radiation and temperature tolerance) from nation's focus on terrestrial renewable energy sources and their associated conversion and distribution functions. In addition, with respect to lowered switching /conduction loss, increased temperature and radiation tolerance, new materials for semiconductor parts should be further explored such as the advances currently in work on SiC active switches. This kind of revolutionary advance in the State of the Art could result in significantly reduced internally generated losses while at the same time improve the junction temperature limit by a factor or 4x or more. The compound effect of these improvements will result in a much smaller and lighter power system particularly when PMAD conversion system magnetic and heat rejection mass are considered. In the area of super capacitors, NASA should sponsor research that would move to hermetically seal the EDLCs, decrease their operating temperature (via a reduction of core to case the thermal resistance), improve their operating voltage, decrease their equivalent series resistance, and ultimately quality this robust design for space applications.

Much of what NASA needs in the area of PMAD, as well as many of the power disciplines are in large part similar to the advances the country needs in its terrestrial green power initiatives that are prevalent in government and venture capital funded R&D efforts today. High voltage, high power, DC distribution systems are center stage as are increased efficiency PV arrays and higher efficiency conversion steps. In addition, the national focus on the smart grid concept (a move away from centralized generation and load aggregation to a distributed interconnected approach) is very much aligned with the advance power management and control techniques NASA will need in future PMAD designs. Future designs that might leverage these new concepts in the terrestrial market to be immensely more efficient in converting their source to electric power and further, be more effective in distributing power and minimizing/reclaiming lost energy. In addition, the smart grid concepts could change the way NASA designs its EPS architectures by reframing the way power designers think of source load interconnection.

2.2.4. Cross-Cutting Technology

Cross-cutting technology is complementary to the power and energy storage technologies while not being directly in line with delivery of an advanced power system itself.

2.2.4.1. Analytical Tools

The development of analytical models and predictive tools to model and characterize subcomponents and systems for power and energy storage are a cross-cutting technology which will provide capability to all NASA missions which require power.

The capabilities needed are physics-based models of all power-related components, sub-systems and whole power systems. Also, needed is an overall algorithm to join the models together to analytically predict the performance of any innovative new technologies and to determine the overall impact on a power system. The analysis could include prediction of overall system efficiency, maximum and minimum power levels, reliability, life, and cost of operation. The models could also help in determining design parameters and the cost of building and testing the prototype, engineering unit, and flight hardware.

Current power system modeling often relies on empirical modeling using experimental data from existing components. The system models are high level and often do not capture the actual impact of new technology when introduced. NASA has in the past (1970's) invested in such analysis tools as the Environmental Workbench, to predict the performance of solar arrays in the space environment. Though effective, commercially developed tools are in use throughout the aerospace industry and other government agencies have worked in this area, no current joint development programs exist. Physics-based models of power system elements and an overall system to connect the models will not be trivial to develop and demonstrate to TRL6. First, it will be necessary to inventory the available models (if any) per power system technology element to determine how they are written, what the inputs/outputs are, how they work in general and how we would like them to work. Then, a gap analysis of the available models needs to be conducted along with how they need to interact and model an entire power system.

2.2.4.2. Green Energy Impact

This section does not address a particular technology, but it involves an approach to energy technology development which is related to power and energy storage. Stimulus to the development of high efficiency, clean power generation and energy storage is probably the most important contribution that NASA's space exploration program can provide to improving the environment and bringing about energy independence for the United

States. Any of the energy technologies developed under this roadmap could find commercial applications and have significant impact despite the differences in performance requirements between aerospace and terrestrial applications. Aerospace applications require maximizing reliability and specific power/energy, while most commercial applications also require minimizing cost and maximizing production capability. NASA's mission requirements create problems which have never before been defined, and the solutions require new thinking and new technology. Thus, NASA's contribution to advances in the energy field result from the efforts to generate novel power systems for NASA needs. This leads to spin-off technologies for the commercial world and the creation of new companies and teams of engineers who will apply NASA's power system technologies to terrestrial needs.

An historical example is the low temperature (e.g., PEM and alkaline) fuel cell. Such fuel cells were a solution in search of a problem until the advent of the human spaceflight program. NASA's interest in fuel cell technology had nothing to do with "alternative energy". The Human Spaceflight Program had no "alternative." In a classic case of "mission pull", NASA had to make fuel cell technology work in order to carry out the Gemini, Apollo, and Shuttle programs. NASA actively funded both PEM and Alkaline technology development through the 1970's. This put technology vendor teams in place in the 1990's to respond to the "green energy" and "hydrogen economy" movements that generated strong interest in PEM fuel cells. In fact, all the major players (automobile companies and power technology firms) can trace their intellectual property heritage and, in some cases, their corporate and technical personnel heritage to the three companies where NASA funded fuel cell development in the 1960's and 70's. NASA in effect created a new industry that brought a laboratory experiment to the current widespread contributions to the energy economy.

Such can happen with any of the technologies being explored on this roadmap. Some especially promising contributions to green energy are photovoltaics, energy storage systems, energy harvesting, power management and distribution (e.g. smart grid), and space nuclear power. NASA's space nuclear power research could contribute to the development of "grid-appropriate" reactors which would allow remote users and small or developing countries to utilize nuclear power instead of power systems that emit CO_2 or other pollutants. NASA work could also contribute to the development of higher efficiency nuclear systems that would reduce excess heat generation as well as reduce the amount of spent fuel generated for a given amount of electricity. NASA thus can make its most effective contributions to solving the world's energy problems by pursuing missions that aggressively pull new technologies out of the laboratory and display them to the world.

2.2.4.3. Multi-Functional Structures

Many NASA missions (cross-cutting) would benefit from the mass reduction resulting from the use of multi-functional structures in the power systems. The idea of incorporating power system elements into the structure of a vehicle or habitat would be beneficial in reducing weight and could also enhance reliability and safety through enhanced capability for redundancy. Current structural elements are not electrically active. However, if power system components and structural elements were designed together in a system with part of the power system providing the structure, or part of the structure providing a power system function, it would be possible to provide "dual use" elements in place of current "single purpose" elements.

One concept would involve using the space/aircraft structure as the electrode materials for batteries. The electrolyte could be sandwiched between two electrode plates which would be part of the structure. This would require the electrodes (anodes and cathodes) to have sufficient strength to bear structural loads. This is clearly possible with the advancement of nanotechnology. For example, carbon nanotubes incorporated in electrodes could provide the strength. The opportunities would probably be greater for a multifunctional structure incorporating super capacitors. Boron nitride (BN) nanotube-based super capacitors are currently of great interest. The structure can be strengthened by BN nanotubes, which can also be used as super capacitors for energy storage. Another possibility is to use the structure as the main power bus bar where the power could pass through the structure and could automatically find the path of least resistance and could "heal" itself if damaged. In effect, it could be a "smart structure".

For a multifunctional structure incorporating super capacitors, it would be necessary to first demonstrate concept feasibility (to TRL 3) in three years, complete subcomponent testing in six years and provide a concept demonstration in ten years. For multifunctional materials that can bear load and act as electrode materials, initial materials could be developed in five years, then a structural sub-system demonstrated in six years and a system level demonstration performed in 10-12 years. Also, nanotube-based super capacitors will provide novel high energy density future energy storage capability as well as being excellent candidates for inclusion in multi-functional structures.

2.2.4.4. Alternative Fuels

Alternative fuels could greatly impact the generation of power. For instance, if a novel way to produce energy dense biomass fuels were available to be produced on the moon or on Mars, then that could become a source of energy for producing power. If a novel in-situ resource became available to generate a new fuel, then that fuel could be used in a power generation system. One major issue facing the space nuclear community is the scarcity of ^{238}Pu. If a viable alternative fuel could be discovered, or if a novel process for generating ^{238}Pu were discovered, this would have a major impact on how we power our future space missions.

3. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

NASA's work in space power and energy storage could have great benefits to other national needs such as the benefits to national defense. Some example applications would be the use of fuel cells, batteries and wireless power transmission to unmanned aerial vehicles for longer flights before refueling and quieter operation. Also, unmanned electric submarines could also benefit from advanced batteries, fuel cells and PMAD systems. Portable power systems for the soldier would be very beneficial by providing lightweight, possibly solar-powered systems to keep the soldier cool and power tools, lights, and computers without relying on a delivery truck to supply fuel or a load of new batteries.

Another visible national need is for energy independence and green energy (discussed previously). NASA's work on batteries and fuel cells and possibly PMAD could have spin-offs to all electric and hybrid cars. Grid scale energy storage systems would benefit from improved batteries, electrolyzers, fuel cells, flywheels, and PMAD. The "Smart Grid" would take advantage of PMAD and Analytical Tools developed to design planetary outpost power systems and terrestrial solar power systems which would consist of high efficiency solar cells, advanced arrays, solar concentrators, and Stirling convertors. Advanced nuclear power systems could benefit from NASA's efforts to design modern, lightweight, novel fission and fusion power systems. Green energy systems would benefit from

Table 2. *Interdependencies with other technology areas*

Relevant Technology Areas	Deliverables or Requirements
Launch Propulsion Systems (TA 1)	High reliability, autonomous, high specific power, long life power and energy storage systems are needed for launch vehicles.
In-Space Propulsion Systems (TA 2)	High Power Systems (100 kW–5 MW) for electric propulsion; Fuel cell power from liquid propulsion reactants; Fusion beam power for plasma thrusters.
Robotics, Tele-robotics, and Autonomous Systems (TA 4)	High specific Energy Storage Systems (>500 Wh/kg); High specific power nuclear and solar power systems
Communication and Navigation Systems (TA 5)	Communications systems produce clearer, more data-rich signals when enabled with high power sources. Long-life power and energy storage are critical to communication and navigation.
Human Health, Life Support and Habitation Systems (TA 6)	EVA Power Systems; Human Habitat Power Systems; Efficient electrolyzers for producing O_2 from water.
Human Exploration Surface Systems (TA 7)	Very high power and energy storage requirements are needed to support human exploration—such as drilling, crewed rovers, high powered instrumentation, etc.
Scientific Instruments, Observatories, and Sensor Systems (TA 8)	Require very long life, ultra reliable, both low and high power systems with high specific energy storage capability and innovations in power scavenging and beaming.
Entry, Descent, & Landing (TA 9)	High g power systems (e.g., low power nuclear; and rugged, deployable, high temperature solar arrays) are required.
Nanotechnology (TA 10)	TA 3 needs input from TA 10 for high specific energy batteries materials, fuel cell catalysts, thermo-electric and photovoltaic materials, etc.
Modeling, Simulation, Information technology and Processing (TA 11)	TA 3 needs to collaborate with TA 11 to generate power and energy storage physics-based models that can be incorporated into a full system simulation.
Materials, Structural and Mechanical Systems, and Manufacturing (TA 12)	Novel, efficient, multi-functional structures with imbedded power systems and high specific power solar arrays are needed from TA 12.
Ground and Launch Systems Processing (TA 13)	High reliability, autonomous, high specific power, long life power and energy storage systems are needed for launch systems. Also: innovative, renewable, portable systems.
Thermal Management Systems (TA 14)	Advances in power and energy storage systems require advanced thermal management technology, such as advanced radiators, heat pipes, Stirling coolers, etc.

NASA's work on alternative fuels for aviation, advanced PMAD for wind/solar systems, and energy conservation analysis. Remote, off-grid power systems could be patterned after NASA's crewed vehicles and habitats.

4. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The interdependencies with other technology areas are shown in Table 2.

5. NATIONAL RESEARCH COUNCIL REPORTS

The earlier sections of this document were completed and issued publicly in December, 2010. NASA subsequently tasked the Aeronautics and Space Engineering Board of the National Research Council of the National Academies to perform the following tasks:

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

In addition to a final report that addressed these tasks, NASA also tasked the NRC/ASEB with providing a brief interim report that "addresses high-level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps."

In August, 2011, the NRC/ASEB delivered "An Interim Report on NASA's Draft Space Technology Roadmaps" which, among other things, verified the adequacy of the fourteen Technology Areas as a top-level taxonomy, proposed changes in the technology area breakdown structure (TABS) within many of the TA's, and addressed gaps in the draft roadmaps that go beyond the existing technology area breakdown structure.

On February, 1, 2012, the NRC/ASEB delivered the final report entitled "NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space". The report prioritizes (e.g., high, medium, low) the technologies **within** each of the 14 Technology Areas, and also prioritizes **across** all 14 roadmaps [highest of the high technologies].

The remainder of this section summarizes:

- The changes that the NRC recommended to the TABS presented earlier in this document
- The NRC prioritization of the technologies in this TA, as well as highlights any of this TA's technologies that the NRC ranked as a 'highest of high' technology.
- Salient comments and context, quoted verbatim, from the NRC report that provide important context for understanding their prioritization, findings, or recommendations.

5.1. NRC Recommended Revisions to the TABS

The current roadmap includes three energy storage technologies: batteries, flywheels, and regenerative fuel cells. Two other approaches may also prove feasible for space applications: (1) electric and magnetic field storage and (2) thermal storage (especially for surface power applications). Accordingly, the NRC recommended the structure for this roadmap be modified by adding two new level 3 technologies:

- 3.2.4. Electric and Magnetic Field Storage
- 3.2.5. Thermal Storage

5.2. NRC Prioritization

The panel identified four top technical challenges for TA03 in priority order:

1. **Power Availability:** Eliminate the constraint of power availability in planning and executing NASA missions.
2. **High-Power for Electric Propulsion:** Provide enabling power system technologies for high-power electric propulsion for large payloads and planetary surface operations.
3. **Reduced Mass:** Reduce the mass and stowed launch volume of space power systems.
4. **Power System Options:** Provide reliable power system options to survive the wide range of environments unique to NASA missions.

The panel evaluated 20 level 3 technologies in

TA03. Six technologies were assessed to be high-priority. The first five technologies were designated as high-priority technologies because they received the highest QFD scores based on the panel's initial assessment. The panel subsequently decided to override the QFD scoring results to designate radioisotope power systems as a sixth high-priority technology to highlight the critical importance of currently funded and planned programs for Pu^{238} production and Stirling engine development and qualification.

- Solar (photovoltaic and thermal)
- Fission
- Distribution and transmission
- Conversion and regulation
- Batteries
- Radioisotope power systems

5.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy :

Solar Power: "Current emphasis is on the development of high-efficiency [solar] cells. NASA also needs: 1) Cells that can effectively operate in low-intensity/low-temperature (LILT) conditions (which are typical when spacecraft are more than three astronomical units from the Sun); 2) Cells and arrays that can operate for long periods at high temperatures (>200°C); 3) High specific power arrays (500 to 1000 W/kg); and 4) Electrostatically clean, radiation tolerant, dust tolerant, and durable, re-stowable and/or deployable arrays."

Fission: "Nuclear reactor systems can provide relatively high power over long periods of time. Space fission technology is currently assessed to be at TRL 3. While some components are demonstrated at higher TRLs, many of the required elements require technology development to advance beyond TRL 3. Other components have reached higher TRLs in past programs such as the SP-100 and Prometheus programs, but technology capability has been lost and must be redeveloped. Key subsystems that must be addressed include the reactor (including instrumentation and control/safety), energy conversion, heat transfer, heat rejection, and radiation shields. NASA is qualified to lead overall systems engineering efforts, with DOE assistance for nuclear subsystems."

Distribution and Transmission: "Proposed research under technology 3.3.3 (D&T) would increase the voltage of D&T subsystems, develop high-frequency AC distribution options for space systems, and identify alternate materials to replace copper conductors. Copper wire has long been a conductor of choice for spacecraft, but as power levels increase, so too will current and voltage and with them the conductor mass will grow. With DC currents, to reduce the mass penalty of larger cables, alternate materials such as superconductors or nano-material conductors may need to be developed, along with lighter space-qualified insulating materials capable of protecting systems at high voltage. With AC power systems, advancing beyond the 116 V AC system in the space shuttle may require very high operating frequencies; for example, NASA funded development of a 440 volt, 20 kHz AC power system for Space Station Freedom until it was reconfigured to use a DC power system (Patel, 2005). Technical needs include keeping transmission losses to a minimum, reducing transformer masses, incorporating fault protection and smart telemetry into power distribution architectures, and developing new connectors."

Conversion and Regulation: "Currently unresolved issues include the need to (1) space-qualify existing terrestrial high-voltage components and (2) replace space-qualified components that currently lag significantly behind the commercial state of the art. Important parameters for improving power conversion and regulation devices include increasing conversion efficiency, operating temperature range, and radiation tolerance."

"An example of advanced conversion and regulation technology is a higher band gap material such as silicon-carbide or gallium-nitride that would replace the traditional silicon materials in switching components, thereby increasing device operating temperature and efficiency while decreasing mass and volume. Another example is advanced magnetics for improved conversion and regulation devices."

"Increasing the efficiency of power conversion could potentially reduce the size of solar arrays, batteries, and thermal control systems by more than 10 percent on lower power systems, with a bigger impact for higher power systems."

Batteries: "NASA is best qualified to lead development of advanced battery technology for their unique mission needs. Ideally, research in this technology would leverage commercial technology developments, as NASA did with the development of Li-ion batteries for space applications. The committee assessed the benefit of battery technology to be significant due to the potential to reduce mass for many space systems and to enable missions in extreme environment missions. NASA can capitalize on the investments by other government and commercial organizations that are making substantial investments in advanced battery technologies. However, the unique requirements posed by NASA missions in extreme environments do require NASA-specific research and development with moderate risk."

Radioisotope: "Future Radioisotope power systems (RPSs) could be developed to deliver both lower power levels (watts or fractions of a watt) and higher power levels (hundreds of watts up to 1 kW). The higher power systems would enable radioisotope electric propulsion for deep space missions, making several new classes of missions possible."

"While RPSs have a well-established foundation, there are significant technology issues that must be overcome to maximize the effectiveness of the United States' dwindling supply of available Pu^{238}."

"Establishing a reliable, recurring source of Pu^{238} and maturing Stirling engine technology are both critically important to provide power for NASA's future science and exploration missions that cannot rely on solar power. ...Although some components have been demonstrated at higher TRLs, a flight test is needed to advance beyond TRL 6."

"The panel assumed that Pu^{238} production and Stirling technology development would continue as currently planned by NASA. As noted above, RPS technology was selected as a high-priority technology despite its relatively modest QFD score because this technology is critically important to the future of NASA's deep space missions. The committee assessed the benefit of additional investments in RPS technology to be low because there are few good options with the potential to improve on the performance of RPSs that couple Stirling engines with Pu^{238} heat sources. However, as noted above, this rating would be much higher if those technologies were not already being developed. Thus, RPS technology would be assessed as a medium priority technology based on its QFD score, which is based on two assumptions: (1) the current program for Stirling engine development is continued and (2) domestic production of Pu^{238} is restored in a timely fashion. Given that the second assumption remains in doubt, the panel overrode the QFD score to assign this technology a high priority."

Comments on the "lower priority" technologies:

"Seven of the eight technologies that were assessed to be low priority were judged to have marginal benefits to NASA missions within the next 20 to 30 years. These technologies included energy harvesting, flywheels, regenerative fuel cells, electric and magnetic field storage, green energy Impact, wireless power transmission, and alternative fuels. The marginal benefit (less than 10 percent improvement) evaluation was based on an assessment of the expected improvement, at the system level, in the primary parameter of interest for each technology. In most cases, this was improvement in spacecraft mass or reliability that the panel believed could be achieved given reasonable investments in that technology. While higher claims have been made for some of these technologies, such as flywheels or electric and magnetic field storage, the panel's review of available information did not produce any credible technology development paths that would achieve the ambitious performance levels specified in the draft roadmap with reasonable investments. Also, currently available approaches for advancing these technologies tended to have a lower risk level than is usually appropriate for NASA technology investments.

The remaining low-priority technology, fusion, was judged to provide no likely value to NASA in the next 20 to 30 years due to a very low probability of success during that timeframe."

ACRONYMS

αT	Total Specific Mass kg/kW
η	Efficiency
^{238}Pu	Plutonium 238
^{241}Am	Americium 241 (isotope)
ASRG	Advanced Stirling Radioisotope Generator
D-D	Deuterium – Deuterium (fusion reaction)
DRM	Design Reference Mission
D-T	Deuterium – Tritium (fusion reaction)
EDLC	Electric Double Layer Capacitor aka supercapacitor
EPS	Electric Power System
ETDD	Enabling Technology Development and Demonstration
ETDP	Exploration Technology Development Program
EVA	Extravehicular Activity
FDIR	Fault Detection Isolation and Recovery
GPHS	General Purpose Heat Source
HST	Hubble Space telescope
ISIS	Integrated Sensor in Structure
ISS	International Space Station
ITER	International Tokomak Experimental Reactor
kW_e	kilowatts electric
LEO	low earth orbit
LILT	Low Intensity/Low Temperature
MER	Mars Exploration Rover
MHD	Magneto-hydrodynamics
$p\text{-}^{11}B$	Proton – Boron 11 (fusion reaction).
PEBB	Power Electronics Building Blocks
PEM	Proton Exchange Membrane
PMAD	Power Management and Distribution
PV	Photovoltaic
RPC	Remote Power Controller
RPS	Radioisotope power system
SEP	Solar Electric Propulsion
SiC	Silicon Carbide
SLA	Stretched Lens Array
SOFC	Solid Oxide Fuel Cell
TDU	Technology Demonstration Unit
TRL	Technology Readiness Level
UAV	unmanned aerial vehicle
UF_4	A cermet fuel
TABS	Technology Area Breakdown Structure
W-UN	Tungsten Uranium

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